SOL-GEL SCIENCE

The Physics and Chemistry of Sol-Gel Processing

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1. SOL-GEL PROCESSING

A *colloid* is a suspension in which the dispersed phase is so small (~ 1–1000 nm) that gravitational forces are negligible and interactions are dominated by short-range forces, such as van der Waals attraction and surface charges. The inertia of the dispersed phase is small enough that it exhibits *Brownian motion* (or *Brownian diffusion*), a random walk driven by momentum imparted by collisions with molecules of the suspending medium. A *sol* is a colloidal suspension of solid particles in a liquid. An *aerosol* is a colloidal suspension of particles in a gas (the suspension may be called a *fog* if the particles are liquid and a *smoke* if they are solid) and an *emulsion* is a suspension of liquid droplets in another liquid. All of these types of colloids can be used to generate polymers or particles from which ceramic materials can be made. A *ceramic* is usually defined by saying what it is *not*: it is nonmetallic and inorganic; some would also say it is not a chalcogenide. We thus include all metal oxides, nitrides, and carbides, both crystalline and noncrystalline. In the sol-gel process, the *precursors* (starting compounds) for preparation of a colloid consist of a metal or metalloid element surrounded by various *ligands* (appendages *not* including another metal or metalloid atom). For example, common precursors for aluminum oxide include *inorganic* (containing no carbon) salts such as $Al(NO_3)_3$ and *organic* compounds such as $Al(OC_4H_9)_3$. The latter is an example of an *alkoxide*, the class of precursors most widely used in sol-gel research. An *alkane* is a molecule containing only carbon and hydrogen linked exclusively by single bonds, as in *methane* (CH_4) and *ethane* (C_2H_6); the general formula is C_nH_{2n+2}. An *alkyl* is a ligand formed by removing one hydrogen (proton) from an alkane molecule producing, for example, *methyl* ($\bullet CH_3$) or *ethyl* ($\bullet C_2H_5$) (where the dot • indicates an electron that is available to form a bond). An *alcohol* is a molecule formed by adding a *hydroxyl* (OH) group to an alkyl (or other) molecule, as in *methanol* (CH_3OH) or *ethanol* (C_2H_5OH). An *alkoxy* is a ligand formed by removing a proton from the hydroxyl on an alcohol, as in *methoxy* ($\bullet OCH_3$) or *ethoxy* ($\bullet OC_2H_5$). A list of the most commonly used alkoxy ligands is presented in Table 1.

Metal alkoxides are members of the family of *metalorganic* compounds, which have an organic ligand attached to a metal or metalloid atom. The most thoroughly studied example is silicon tetraethoxide (or tetraethoxysilane, or tetraethyl orthosilicate, TEOS), $Si(OC_2H_5)_4$. *Organometallic* compounds are defined as having direct metal–carbon bonds, not metal–oxygen–carbon linkages as in metal alkoxides; thus, alkoxides are not organometallic compounds, although that usage turns up frequently in the

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